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Disturbance Rejection for a Third Order Process Controlled by a PD-PI Controller

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The purpose of this paper is to investigate using a PD-PI controller in the disturbance rejection associated with a third order process. The PD-PI controller having four parameters are tuned to provide efficient rejection of a step disturbance input. Controller tuning based on using MATLAB control and optimization toolboxes with five error-based objective functions: ISE, IAE, ITAE, ITSE and ISTSE is implemented. The control system performance during disturbance rejection is evaluated through the maximum value of the step time response, its corresponding time and its settling time. The best objective function is assigned and used to tune the PD-PI controller. The PD-PI controller is superior compared with using a PID and PI-PD controllers to control the same process for the purpose of disturbance rejection.

Keywords: Disturbance rejection; Third order process; PD-PI controller; Controller tuning; Control system performance; MATLAB optimization and control toolboxes.

I. INTRODUCTION

Skogestad (2001) used modified integral term of the PID controller to improve disturbance rejection associated with integrating processes [1]. Skogestad (2003) used a single tuning rule for first order and second order time delay models [2]. Sorensen, et al. (2007) developed a combined feedback and input shaping controller to address sources of oscillation by motion of the bridge or crane or from environmental disturbances. They applied the developed controller on a 10 ton bridge crane of the Georgia Institute of Technology [3]. Jain and Nigam (2008) explored the idea of model generation and optimization for a PD-PI controller. They obtained promising results when using the PD-PI controller with the highly nonlinear inverted pendulum [4]. Matusu, et al. (2009) compared three different control designs for SISO system with harmonically time-varying delay. They compared the three methods through simulation example for both set point tracking and disturbance inputs [5]. Jujuly (2010) developed a unified framework for the internal model control (IMC) based on PI/PID controller design and analysis. He developed a generalized 2DOF IMC-PI/PID controller design methods for first order, second order and other processes without time delay and compared with other existing methods [6]. Asad, et al. (2011) proposed a fuzzy PD-based control strategy to transfer loads using overhead cranes. They presented a comparative analysis of fuzzy PD and classical PD controllers [7]. Rajinikanth and Lathe (2012) proposed a bacterial foraging optimization algorithm based approach to tune an IMC-PID controller for a class of first order plus time delayed unstable systems. They confirmed the efficiency of their tuning procedure through a comparison with other algorithms such as particle swarm optimization and ant colony optimization. They obtained robust performance in reference tracking with perturbed model parameters [8].

Herbst (2013) carried out a simulative study using generic first and second order plants for quick virtual assessment of the abilities of disturbance rejection control. He concluded that active disturbance rejection control can be considered as a strong alternative for solving practical control problems [9]. Agarwal (2013) proposed tuning rules for PI and PID controllers for unstable first order plus dead time processes. His tuning method is based on the satisfaction of gain and phase margin specifications [10]. Hassaan (2014) used a PI-PD controller to control a highly oscillating second order process for set point tracking. He used an ISE objective function to tune the controller using MATLAB optimization. He compared his results with another tuning technique where he has got spike free time response [11]. Kumar and Patel (2015) presented a design approach for 2DOF PID controllers for second order processes without time delay. They compared control system dynamics using the 2DOF PID controller with that using a classical PID controller [12]. Hassaan (2015) investigated using a number of controllers belonging to the second generation of PID controllers in the rejection of the disturbance associated with a highly oscillating second order process. His work covered using a PI-PD controller [13], a feedforward second order compensator [14] and a PD-PI controller [15]. He stated that the PD-PI controller is superior in dealing with the disturbance rejection associated with the highly oscillating second order process [15]. His studies covered also using a PID plus First-order lag controller in disturbance rejection associated with delayed double integrating process [16], a 2DOF PID-PI controller [17], a 2DOF controller in disturbance rejection associated with delayed double integrating processes [18], a PI-P controller for the purpose of disturbance rejection associated with delayed double integrating processes [19], a feedback PD compensator for disturbance rejection associated with delayed double integrating processes [20], an I-PD controller for disturbance rejection associated with delayed double integrating processes [21] and a PPI controller for disturbance rejection associated with a highly oscillating second-order process [22].

Shin (2015) presented PID controller with disturbance rejection, low sensitivity and notch filter against bending frequency by the disturbances. They certified the performance of the designed system by simulation and experimentally indicating the improvement of system performance in cases of existence of external disturbances [23].

Li Sun et al (2016) showed that a certain relative delay margin can represent the robustness level well and the contour can be sketched with a simpler procedure than the one using maximum sensitivity index. With constraints on the relative delay margin, an optimal disturbance rejection problem is then formulated and analytically solved [24]. Jan Cvejn (2017) enhanced the disturbance-rejection performance of the Magnitude Optimum (MO) tuning method for PI controllers means of additional filter designed so that the stability margin properties of the MO tuning are preserved [25]. Tavakoli, Sadeghi, Griffin and Fleming (2016) presented a method for tuning PI controller. The design technique was based on optimization of load disturbance rejection with a constraint either on the gain margin or phase margin [26]. Niu, Gao, Liu, Tang and Guan (2019) introduced a linear active disturbance rejection control (LADRC). As comparisons, they indicated that reduced-order LADRC can realize higher trajectory tracking accuracy with low-resolution encoder and has better robustness to variation in erection loads, compared with traditional LADRC and PID with HGTD [27]. Liu, Gao, Chen and Liu (2020) presented linear active disturbance rejection control (LADRC) for a two-degrees-of-freedom (2-DOF) manipulator system to achieve trajectory tracking. They indicated that the superiority of LADRC over the PID for trajectory tracking and dynamic performance. [28]

II. PROPOSED ALGORITHM

2.1 The Process

The process considered in this analysis is a third order process having the following transfer function [29]:

$$G_p(s) = K_{ip} / [(T_1T_2)\, s^3 + (T_1+T_2)\, s^2 + s + K_{ip}] \qquad (1)$$

where

K_{ip} integral gain of the process ($K_{ip} = 0.5$)

T_1 ...Process time constant ($T_1 = 1$ s)

T_2 ...Process time constant ($T_2 = 5$ s)

2.2 The PD-PI Controller

The controller used in this study is a proportional + derivative (PD) - proportional + integral (PI) controller. In this controller, The PD and PI parts of the controller are connected in series. The input to the PD part is the system error, while the input of the PI part is the output of the PD part as shown in Fig. 1 [30].

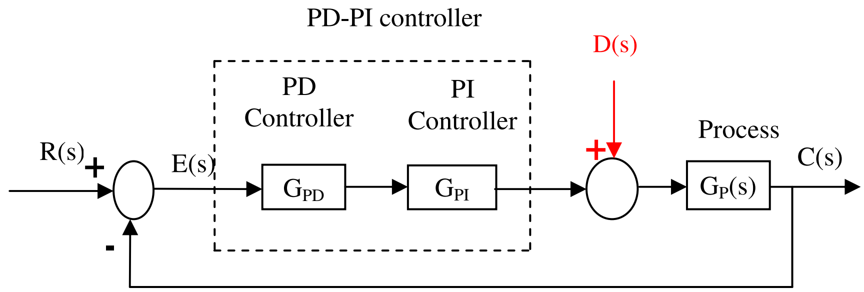

Figure 1 Block diagram incorporating a PD-PI controller [25]

The block diagram of the control system of Fig. 1 has two inputs: reference input R(s) and disturbance input D(s) and one output variable C(s). This PD-PI controller has four parameters to be tuned to get optimal performance for the control system and therefore disturbance rejection.

2.3 Closed-loop Transfer Function

The dynamics of the closed-loop control system depends on its transfer function between its input and output. For the purpose of disturbance rejection investigation, the reference input R(s) is omitted from Fig.1 and the disturbance input D(s) is considered the control system input. The new block diagram of the control system in this case is shown in Fig.2.

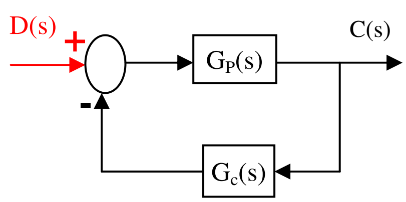

Figure 2 Control system block diagram with disturbance input

Where

$G_c(s)$ ... Open-loop Transfer function of the PD-PI controller.

$$G_c(s) = (k_{pc1}+k_d.s)[k_{pc2}+(k_i / s)] \quad (2)$$

The closed-loop transfer function of the control system C(s) / D(s) is obtained from the system block diagram of Fig.2 and Eqs.1 and 2 as:

$$C(s) / D(s) = b_0 s / [a_0 s^4+a_1 s^3+a_2 s^2+a_3 s+a_4] \quad (3)$$

Where

$b_0 = K_{ip}$

$a_0 = T_1T_2$, $a_1 = T_1+T_2$, $a_2 = K_{pc2}K_{ip}K_d+1$, $a_3 = K_{ip}K_{pc1}K_{pc2}+K_{ip}K_iK_d+K_{ip}$,

$a_4 = K_{ip}K_iK_{pc1}$

Eq.3 reveals an important fact regarding the dynamics of the control system during disturbance rejection. The presence of the parameter (s) in the numerator of the transfer function results in a zero steady-state response of the control system to a step disturbance input. This means that the steady-state error of the system is also zero which is the first success in using the PD-PI controller for disturbance rejection of the highly oscillating process. The characteristics of the time response transients will be left to the controller tuning to provide optimal time response with good performance.

2.4 Controller Tuning and System Step Time Response

The PD-PI controller has four parameters: K_{pc1}, K_{pc2}, K_i, K_d. which were tuned by authors using MATLAB control and optimization toolboxes for a reference input condition [30]. The control toolbox is used to estimate the time response of the control system for a unit disturbance input for any set of controller parameters using its command '*step*' [31, 32]. The optimization toolbox is used to minimize an error-based objective function through its command '*fmincon*' [33]. Five error based objective functions are used in tuning the controller which are: ISE, IAE, ITAE, ITSE and ISTSE [34-38]. Fig.3 gives the unit step time response of the control system for disturbance rejection. As shown in Fig.3 the time response of the control system tuned with the IAE has better characteristics than the other objective functions (except the ISE having almost the same step time response).The tuned parameters of the

PD-PI controller are:

$K_{pc1} = 0.2987$, $K_d = 4.0009$, $K_{pc2} = 7.9996$ and $K_i = 4.0003$.

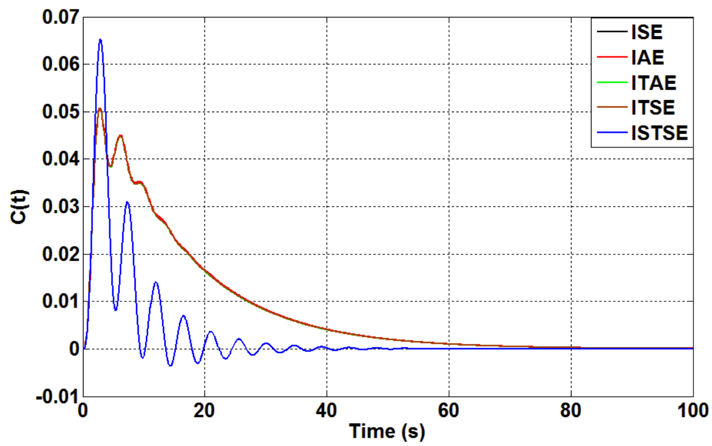

Figure 3 Comparison between time responses using five objective functions

III. COMPARISON WITH OTHER CONTROLLERS

To judge the effectiveness of using the PD-PI controller for disturbance rejection associated with the third order process, it has been compared using the same process with a tuned PID controller and a tuned PI-PD controller tuned by the authors in other work [38]. Fig.4 shows a comparison between the time responses of the control system during disturbance rejection using the three different controllers: PD-PI (present), PI-PD and PID controllers.

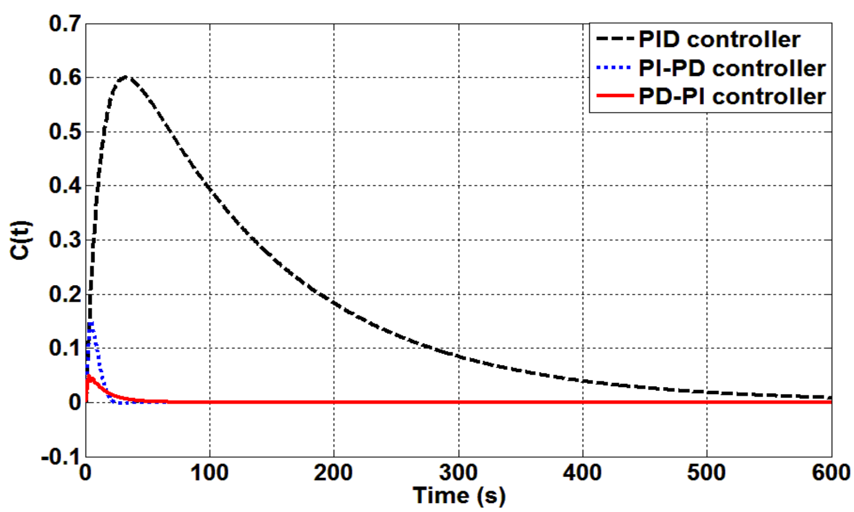

Figure 4 Comparison between time responses using PD-PI, PID and PI-PD controllers.

The time based specifications of the control system for disturbance rejection are compared in Table 1.

Table 1: Time based specifications of the control system using PID, PD-PI and PI-PD controllers

Parameters	PID controller	PD-PI controller	PI-PD controller
c_{max}	0.6	0.0508	0.15
T_{cmax} (s)	33.3	2.8	4.6
T_s (s)	489	17.5	18.5

It is clear from Table 1 and Fig.4 if the PD-PI controller can compete both the PI-PD and the PID controllers in disturbance rejection of the third order process. The settling time is evaluated as the time after which the time response due to a unit disturbance input stays within a value of ± 0.02. The values of the maximum time response c_{max}, time of maximum response T_{cmax} and settling time T_s, all indicate the effectiveness of using the PD-PI controller for disturbance rejection. The tuned parameters of the PID controller are: K_p(PID) = 0.4342, K_i(PID) = 0.01, K_d(PID)= 14.97. The tuned parameters of the PI-PD controller are: K_{pc1}(PI-PD) = 0.0698, K_d (PI-PD) = 15.1293, K_{pc2} (PI-PD) = 5.3926, K_i (PI-PD) = 0.6982.

IV. CONCLUSION

- The possibility of using PD-PI controller for disturbance rejection associated with a third order process was investigated.
- The controller was tuned to adjust its four parameters for optimal performance using five objective functions and the MATLAB optimization toolbox.
- The best objective function was assigned which was the IAE objective function.
- The PD-PI controller could generate disturbance response of maximum value as low as 0.05 and time of maximum disturbance time response as low as 3 s.
- The performance of the closed loop control system for disturbance rejection using a PD-PI controller was compared with that using PID and PI-PD controllers for the same process.
- The PD-PI controller was superior compared with the PID and PI-PD controllers in rejecting the disturbance associated with the third order process.

REFERENCES

[1] S. Skogestad, "Probably the best simple PID tuning rules in the world." AIChE Annual Meeting, Reno, Nevada, p. 27, 2001.

[2] S. Skogestad, "Simple analytic rules for model reduction and PID controller tuning." Journal of Process Control, vol. 13, pp. 291-309, 2003.

[3] K. Sorensen, W. Singhose and S. Dickerson, "A controller enabling precise positioning and sway reduction in bridge and gantry cranes." Control Engineering Practice, vol. 15, pp. 825-837, 2007.

[4] T. Jain and M. Nigram, "Optimization of PD-PI controller using swarm intelligence." Journal of Theoretical and Applied Information Technology, vol. 6, pp. 55-59, 2008.

[5] R. Matusu, R. Prokop and J. Vojtesek, "Control of systems with time varying delay: an algebraic approach versus modified Smith predictors." In 17th International Conference on Process Control.Strbske Pleso, Slovakia. p. 5, 2009.

[6] M. Jujuly, "Analytical design of PID controller for enhanced disturbance rejection of processes without time delay." M. Sc., Department of Chemical Engineering and Technology, Graduate school of Yeungnam University. South Korea, 2010.

[7] S. Asad, M. Salahat, M. AbuZalata, M. Alia and A. Al-Rawashdeh, "Design of fuzzy PD controlled overhead crane system with anti-swing compensator." Journal of Engineering and Computer Innovations, vol. 2, pp. 51-58, 2011.

[8] V. Rajinikanth and K. Lathe, "Internal model control-PID controller tuning for first order plus time delayed unstable systems using bacterial foraging algorithm." Scientific Research and Essays, vol. 7, pp. 3406-3420, 2012.

[9] G. Herbst, "A simulative study on active disturbance rejection control as a control tool for practitioners." Electronics, vol. 2, pp. 246-279, 2013.

[10] K. Agarwal, "A paper on system stability (first order and second order) using PID controller." International Journal of Innovative Technology and Engineering, vol. 3, pp. 129-132, 2013.

[11] G. A. Hassaan, "Tuning of a PI-PD controller used with highly oscillating second order process", International Journal of Research in Innovative Technology, vol.1, issue 5, pp.67-69, 2014.

[12] M. Kumar and V. Patel, "Tuning of two degree of freedom PID controller for second order processes", International Journal of Science, Engineering and Technology Research, vol.4, issue 5, pp.1543-1546, 2015.

[13] G. A. Hassaan, " Disturbance rejection associated with a highly oscillating second-order-like process; part I: feedforward second-order compensator", International Journal of Computer Techniques, vol. 2, issue 4, pp. 90-95, July 2015.

[14] G. A. Hassaan, " Disturbance rejection associated with a highly oscillating second-order process; part II: PD-PI controller", Academic Research Publishing Group, vol. 1, issue 7, pp. 102-107, July 2015.

[15] G. A. Hassaan, “Disturbance rejection with a highly oscillating second-order-like process, Part III: PI-PD controller”, Journal of Research in Science Technology Engineering and Management, vol.1, Issue 1, pp. 53-58, 2015

[16] G. A. Hassaan, "Controller tuning for disturbance rejection associated with delayed double integrating process, Part IV: PID plus first order lag controller." International Journal of Advanced Research in Compute Science & Technology, vol. 3, issue 3, pp. 67-71, July 2015.

[17] G. A. Hassaan, "Disturbance rejection with highly oscillating second-order-like process, part V: 2DOF PID-PI controller " International Journal of Engineering and Advanced Research Technology, vol. 1, issue 3, pp. 19-22, September 2015.

[18] G. A. Hassaan, "Controller tuning for disturbance rejection associated with a delayed double integrating process, Part V: 2DOF controller." International Journal of Engineering and Technology, vol. 1, issue 3, pp. 26-31, September 2015.

[19] G. A. Hassaan, "Controller tuning for disturbance rejection associated with delayed double integrating process, Part VI: PI-P controller." International Journal of Advanced Research in Management, Architecture, Technology and Engineerig (IJARMATE), vol. 1, issue 1, pp. 1-5, August 2015.

[20] G. A. Hassaan, " Compensator tuning for disturbance rejection.associated with delayed double integrating processes, part 1: feed-back PD conpenstaror" ,World Journal of Engineering research and Technology (WJERT), vol. 1, issue 1, pp. 27-36, 2015.

[21] G. A. Hassaan, “Controller tuning for disturbance rejection associated with delayed double integrating processes, Part II: I-PD controller”, International Journal of Science and Engineering, vol.1, issue 3, pp.1-8, 2015.

[22] G. A. Hassaan, “ Disturbance rejectionwith a highly oscillating second-order-like processes, part VI:PPI controller”, International Journal of Science and Engineering, vol.1, issue 9, pp.20-27, 2015.

[23] K. Shin, "Design and implementation of dynamic attitude control of continuous track system using gyro sensors." International Journal of Control and Automation, vol. 8, pp. 221-230, 2015.

[24] L. Sun, D. Li and K. LEE, "Optimal disturbance rejection for PI controller with constraints on relative delay margin", ISA Transcations, vol.63, pp.103-111, July 2016.

[25] J. Cvejn, "Enhancing disturbance rejection performance for the magnitude-optimum-tuned PI controller ", 21st International Conference on Process Control, Slovakia, June 2017.

[26] S. Tavakoli, J. Sadeghi, I. Griffin and P.J. Fleming, " PI controller tuning for load disturbance rejection using constrained optimization ", International Journal Dynamics control, vol.6, issue 1, pp.188-199, 2018.

[27] H. Niu, Q. Gao, Z. Liu, S.Tang and W. Guan, " Improved linear active disturbance rejection control for lever-type electric erection system with varying loads andlow-resolution encoder ", Mathematical Problems in Engineering, vol.2019, Article ID 9867467, 13 pages, 2019.

[28] D. Liu, Q. Gao, Z. Chen and Z. Liu, "Linear Active Disturbance Rejection Control of a Two-Degrees-of-Freedom Manipulator", Mathematical Problems in Engineering, vol.2020, Article ID 6969207, 19 pages, 2020.

[29] A. F. Singer, G. A. Hassaan and M. A. Elgamil, "Tuning of a PI-PD controller used with a Third Ordr Process", World Journal of Engineering Research and Technology (WJERT),vol. 6, issue 4, pp. 367-375, 2020.

[30] A. F. Singer, G. A. Hassaan and M. A. Elgamil, "Tuning Of a PD-PI Controller Used With a Third Order Process", International Journal of Application or Innovation in Engineering &Management(IJAIM),Vol.9, Issue 8, 2020".

[31] C. Lopez, Control Systems with MATLAB: Springer, 2014.

[32] C. Houpis and C. Sheldon, Linear control analysis and design with MATLAB, CRC Press, 2013.

[33] P. Venkataraman, Applied optimization with MATLAB programming, J. Wiley and Sons, 2009.

[34] D. Xue, Y. Chen and D. Atherton, "Linear feedback control: Analysis and design with MATLAB, Society for Industrial and Applied Mathematics, 2007.

[35] V. Soni and R. Bhatt, “BF, PSO optimization PID controller design using ISE, IAE, IATE and MSE error criteria”, International Journal of Advanced Research in Computer Engineering and Technology, vol.2, issue 7, pp.2333-2336, 2013.

[36] M. Martins, "Tuning PID controllers using ITAE criterion." International Journal of Engineering Education, vol. 21, pp. 867-873, 2005.

[37] M. Khalilpour, K. Valipour, N. Shayeghi and N. Razmjooy, “Designing a robust and adaptive PID controller for gas turbine connected to the generator”, Research Journal of Applied Science, Engineering and Technology, vol.5, issue 5, pp.1544-1551, 2013.

[38] A. F. Singer, G. A. Hassaan and M. A. Elgamil, "Disturbance rejection for a third order process controlled by a PI-PD controller", International Journal of Mechanical Engineering and Technology (IJMET),vol. 11, issue 8, pp. 1-7, 2020.